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博　士　学　位　论　文

载波电子散斑干涉测量关键技术及其在光声成像中的应用研究

Research on Key Technologies of Carrier Electronic Speckle Pattern Interferometry and the Application in Photoacoustic Imaging

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摘 要

电子散斑干涉测量技术（Electronic Speckle Pattern Interferometry, ESPI）作为一种对光学粗糙表面进行全场无损测量的技术，已被广泛地应用于应变、位移、振动和医学诊断等方面的测量。载波电子散斑干涉（Carrier Electronic Speckle Pattern Interferometry, CESPI）作为 ESPI 的一种，只需一幅或两幅被测物体的载波相关条纹图便能解调出高精度的离面位移量，特别适合于物体动态变形场的无损测量和分析。尽管 CESPI 代表了电子散斑干涉测量的一个重要发展方向，但目前关于高精度的 CESPI 技术及其在动态测量中的应用研究仍不成熟。

本论文通过对 CESPI 相关条纹调制和解调的关键技术进行深入的研究，提出了关于提高系统测量精度的一系列新方法，研制了一套基于载波 ESPI 的高频离面振动测量系统。

论文首先针对传统的光程差分析法以点代面分析像面散斑，存在无法真实反映散斑光场全局信息的局限性，通过建立 CESPI 菲涅耳衍射数学模型，研究载波调制时整个像面散斑场的复振幅变化规律，并基于该规律解释了调制原理；研究了影响相关条纹图质量的重要因素，提出了载波频率的选择原则以及获得理想相关条纹对比度应注意的几个事项。

分析比较了空域滤波、旋滤波和频域滤波方法，提出了四种带通同态滤波方法，实验结果表明这四种滤波器能有效去除散斑乘性噪声；结合该滤波技术，进行 Fourier 变换相位解调能获得理想的全场三维离面位移图；提出了形貌相减消差法和旁瓣共轭消差法，用于完全消除谱旁瓣偏移误差产生的误差，有效提高测量精度；研究了基于条纹中心线法的解调原理和方法；通过 Fourier 变换相位解调和中心线法解调三维离面位移图亚像素重建技术，进一步提高了系统测量精度。

将 CESPI 技术和脉冲曝光散斑干涉技术相结合，设计了一种基于偏转参考镜面的 CESPI 高频离面振动测量系统。

同时，鉴于 CESPI 具有全场、非接触、高精度、快速、可实时检测的优点，本文研究了 CESPI 在生物组织光声成像中应用的可行性。根据光声信号在薄膜中的传输机理，设计了一种基于 ESPI 的传感薄膜探测器；进而提出并设计了一

种基于 CESPI 的新型生物组织光声成像系统。

这些研究结果具有重要的参考价值，不仅为高精度的静态位移测量和动态振动测量提供了新的方法，也为 CESPI 技术在新型生物组织光声成像系统的下一步应用研究提供理论基础。

本文的主要创新点如下：

1. 通过建立CESPI的菲涅耳衍射数学模型，解释了CESPI相关条纹的调制原理。相比传统的光程差法，这种方法更加科学、严谨。

2. 提出了CESPI相关条纹的四种带通同态滤波器——理想带通同态滤波器、高斯带通同态滤波器、n阶巴特沃思带通同态滤波器和指数带通同态滤波器。提出了将带通同态滤波和Fourier变换以及形貌相减消差法和旁瓣共轭消差法相结合进行相位解调的方法，可完全消除频谱旁瓣偏移引起的测量误差，获得高精度的全场离面位移量信息。

3. 首次提出基于载波条纹调制方向的 CESPI 相关条纹中心线提取算法及相应的边沿条纹中心线补充法算法，并结合亚像素定位技术，提出了基于条纹中心线提取的离面位移图像的亚像素重建方法。该方法通过精确定位中心线的亚像素位置，显著地提高中心线上各点离面位移的测量精度，具有简便可行、测量精度高等优点。

4. 采用低速摄像装置研制了一套基于偏转参考镜面的CESPI高频离面振动测量系统，实现了高频（$\geq 10kHz$）离面振动的测量。偏转参考镜面载波调制能有效增大调制频率，有利于包含变形信息的载波频谱成分和背景低频频谱成分的分离，保证了系统的测量精度。

5. 率先对 ESPI 在生物组织光声成像中的应用进行了试探性研究，首次提出并设计了一种基于 CESPI 的新型光声成像系统。该系统采用一种基于 ESPI 的传感薄膜探测器替代传统的压电式传感器。研究表明，这种新的成像方法有望提供一种可实现全场、后向检测模式、三维成像、高分辨率的全光路检测生物组织医学成像技术。

关键词： 载波电子散斑干涉；光声成像；离面振动；条纹中心线；亚像素

ABSTRACT

Being a whole-field and non-destructive technique to measure the optical rough surface, Electronic Speckle Pattern Interferometry (ESPI) has been widely used in the measuring of strain, displacement, vibration and medical diagnosis. Carrier Electronic Speckle Pattern Interferometry (CESPI) is one kind technique of ESPI. Because CESPI only needs one or two pieces of carrier correlation fringe images to demodulate out-of plane displacement of the testing object with high precision, it is very adequate for objiect dynamic nondestructive measurement and analysis. Through CESPI represents one of improtant development direction of ESPI, researchs of CESPI technology and application in dynamic measurement are still immature.

This paper makes an intensive study on the key modulation technology and demodulation technology of CESPI correlation fringe. A series of new methods to improve measurement precision and is proposed. A set of measurement system for out-of plane vibration with high frequency based on CESPI is developed.

Firstly, the traditional optical path difference analysis method taking optical path change of one point as the whole surface's couldn't reflect the basic characteristic really that the speckle field on the image surface was composed by the scattered light of the whole objiect surface. In order to overcome the limitation caused by the traditional optical, a Fresnel diffraction mathematics model of CESPI is built to study the change law of plural amplitude expressing the speckle field of the whole objiect surface at the time of modulation. The modulation principle of CESPI correlation fringes is interpreted by the change law. The important factors having effect on the quality of correlation fringe image are researched. Then a choice rule of carrier frequency and the matters needing attention how to get ideal contrast of correlation fringe are advanced.

After analysing spatial domain filter method, Spin filter method, frequency domain filter method, four different CESPI filters based on frequency domain homomorphic filtering are established. The result of experiments shows that these filters can eliminate the multiplicative noise effectively. Using the means combined frequency domain homomorphic filtering to make Fourier transform phase demodulation, we can obtain ideal whole 3D out-of plane displacement image. In order to advoid measuring error caused by frequency spectrum side band's center excursion and improve measuring precision, apperance subtraction method and conjugated side band method are proposed. The demodulation principle and method based on CESPI fringe skeleton are studied. Through sub-pixel reconstruction method based on Fourier transform and sub-pixel reconstruction method based on correlation fringe skeletons, it can further improve the measuring precision.

Combined CESPI technique and pulse exposal ESPI technique, a set of CESPI measurement system for out-of plane vibration based on deflexion of reference mirror is developed.

At the same time, in view of the advantages of CESPI including whole field, non-contact, high-resolution, celerity and real-time detection, the feasibility that applying CESPI in photoacoustic imaging of biological tissue is discussed. Based on the photoacoustic signal transmission principle through film, a sensor film detector based on ESPI is designed. Furthermore, a new photoacoustic imaging system based on CESPI is presented and designed.

These research results have important reference valve. They ont only offer a new method for the applications in static displacement measurement and dynamic vibration measurement with high precision, but also provide the farther application study on new photoacoustic imaging system of biological tissue with academic basic.

The innovations of this dissertation are as follows:

1. Throug building Fresnel diffraction mathematics model of CESPI, the modulation principle of CESPI correlation fringes is interpreted. The method is more scientifical and accurate than the traditional optical path difference analysis method.

2. Four different homomorphic filters are established for CESPI correlation fringe. They are ideal homomorphic filtering with band-pass filter, Gauss homomorphic filtering with band-pass filter, n rank Brtterworth homomorphic filtering

with band-pass filter and exponent homomorphic filtering with band-pass filter. A phase demodulation method combined with frequency domain homomorphic filtering, Fourier transform, apperance subtraction method and conjugated side band method is proposed. It can eliminate the measurement error caused by frequency spectrum side band's center excursion entirely, and obtain the whole 3D out-of plane displacement image and imformation with high precision.

3. The extraction algorithm of CESPI fringe skeleton which based on the modulation direction of carrier fringe and the compensation algorithms for the marginal fringe skeleton are first presented. Combined with sub-pixel orientation technology, a sub-pixel reconstruction method for out-of plane displacement image is given. By the fringe skeleton sub-pixel orientation, it can improve the measurement precision of the fringe skeleton evidently. The method has some advantages, such as briefness, convenience, high efficiency and high precision.

4. Based on deflexion of reference mirror，an out-of plane high frequency vibration CESPI measurement system using low speed CCD camera is designed. The system can measure high frequency out-of plane vibration whose frequency is higher than $10kHz$. By the carrier modulation method, it can increase the modulation frequency effectively that is propitious to the abruption between the carrier frequency spectrum part including shape change information and the low frequency part including background information. So it provides measuring precision with security.

5. The trial ESPI for photoacoustic imaging of biological tissue is performed. A new kind of photoacoustic imaging system based on CESPI is presented and designed for the first time. A kind of sensor film detector is adopted to replace the ordinary piezoelectricity detectors in this system. The research result shows that the new imaging method will provide a new biomedical imaging technology with a whole field, backward-mode, three-dimensional imaging, high-resolution and all-optical detecting.

Key words: CESPI; Photoacoustic Imaging; Out-of Plane Vibration; Fringe Skeleton; Sub-pixel.

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